

Claims

1. An adaptive control system (ACS) generating at least one control signal  $\delta_e$   
5 to regulate a plant output signal  $y$  by feedback of the plant output signal  $y$ , and  
optionally other sensed variables affecting the state of the plant, the plant output  
signal  $y$  being a function of the full plant state having known but unrestricted relative  
degree  $r$ .

10 2. An ACS as claimed in claim 1 wherein the ACS controls the plant output  
signal  $y$  based on an approximate linear dynamic model, and controls unmodeled  
plant dynamics using adaptive control.

15 3. An ACS as claimed in claim 2 wherein the ACS comprises an adaptive  
element to implement adaptive control of the plant output signal  $y$ , the adaptive  
element comprising a neural network.

20 4. An ACS as claimed in claim 3 wherein the adaptive element uses at least  
one time-delayed version  $y_d$  of the plant output signal  $y$ , that is supplied together with  
the plant output signal  $y$  as inputs to the neural network, the neural network generating  
an adaptive control signal  $v_{ad}$  contributing to generation of the control signal  $\delta_e$  to  
control the plant output  $y$  inspite of unmodeled plant dynamics, based on the time-  
delayed signal  $y_d$  and the plant output signal  $y$ , the time-delayed version signal  $y_d$  and  
the plant output signal  $y$  ensuring boundedness of the tracking error  $\tilde{y}$ .

25 5. An ACS as claimed in claim 3 wherein the neural network of the adaptive  
element comprises at least one basis function  $\phi$  and at least one connection weight  $W$   
used to generate an adaptive control signal  $v_{ad}$  contributing to generation of the  
command control signal  $\delta_e$ , the adaptive element further comprising an error  
30 conditioning element coupled to receive the basis function  $\phi$ , the error conditioning  
element filtering the basis function  $\phi$  with a transfer function  $T^{-1}(s)$  to produce

filtered basis function  $\phi_t$  used to modify the connection weight(s)  $W$  of the neural network through feedback to ensure boundedness of the tracking error  $\tilde{y}$ .

5        6. An ACS as claimed in claim 1 wherein the ACS comprises a command filter unit generating an  $r$ th derivative  $y_c^{(r)}$  of the plant output signal  $y$  in which  $r$  is an integer indicating the number of times the plant output signal  $y$  must be differentiated with respect to time before an explicit dependence on the control variable is revealed.

10      7. An ACS as claimed in claim 1 wherein the ACS comprises:  
an error signal generator generating a tracking error signal  $\tilde{y}$  indicating the difference between the plant output signal  $y$  and a commanded output signal  $y_c$ ;

15      a linear controller coupled to receive the tracking error signal  $\tilde{y}$ , the linear controller generating a transformed signal  $\tilde{y}_{ad}$  based off the tracking error signal  $\tilde{y}$ ; and  
an adaptive element coupled to receive the transformed signal  $\tilde{y}_{ad}$  and generating an adaptive control signal  $v_{ad}$  based thereon, the adaptive element operating on the transformed signal  $\tilde{y}_{ad}$  to generate the adaptive signal  $v_{ad}$  such that the transfer  
20      function from  $v_{ad}$  to  $\tilde{y}_{ad}$  is strictly positive real (SPR).

8. An adaptive control system (ACS) for controlling a plant based on at least one commanded output signal  $y_c$  and an  $r$ th time-derivative of the commanded output signal  $y_c^{(r)}$ , and a plant output signal  $y$  that is a function of the states existing in the plant,  $r$  being the relative degree of the plant output signal  $y$ , the ACS comprising:

- 5        a model inversion unit (MIU) coupled to receive a pseudo-control signal  $v$  and a plant output signal  $y$ , the MIU generating a control signal  $\delta_c$  by inverting an approximate model of the plant dynamics, the MIU supplying the control signal  $\delta_c$  to the plant for control thereof;
- 10        a summing unit coupled to receive the  $r$ th time-derivative of the commanded output signal  $y_c^{(r)}$ , a pseudo-control component signal  $v_{dc}$ , and an adaptive control signal  $v_{ad}$ , the summing unit adding the  $r$ th time-derivative of the commanded output signal  $y_c^{(r)}$  and the pseudo-control component signal  $v_{dc}$ , and subtracting the adaptive control signal  $v_{ad}$ , to generate the pseudo-control signal  $v$ ;
- 15        an error signal generator (ESG) coupled to receive the commanded output signal  $y_c$  and optional derivatives thereof and the plant output signal  $y$ , the ESG generating a tracking error signal  $\tilde{y}$  by differencing corresponding signal components of the commanded output signal  $y_c$  and optional derivatives thereof, and a plant output signal  $y$ ;
- 20        a linear controller having a linear dynamic compensator (LDC) coupled to receive the tracking error signal  $\tilde{y}$ , the LDC generating a pseudo-control component signal  $v_{dc}$  based on the tracking error signal  $\tilde{y}$ , the pseudo-control component signal  $v_{dc}$  for stabilizing the feedback linearized dynamics of the model inverted in the model inversion unit, the LDC generating a transformed signal  $\tilde{y}_{ad}$  based on the tracking error signal  $\tilde{y}$  so that a transfer function from an adaptive control signal  $v_{ad}$  to the transformed signal  $\tilde{y}_{ad}$  is strictly positive real (SPR);
- 25        an adaptive element having
  - an error conditioning element coupled to receive the transformed signal  $\tilde{y}_{ad}$  and at least one neural network basis function  $\phi$ , the error conditioning element stable low-pass filtering the basis function  $\phi$  to produce a

filtered basis function  $\phi_f$  and multiplying the filtered basis function  $\phi_f$  by the transformed signal  $\tilde{y}_{ad}$  to produce a training signal  $\delta$ ; and

5 a neural network adaptive element (NNAE) coupled to receive  
the plant output signal  $y$ , the pseudo-control signal  $v_{ad}$ , and the training signal  $\delta$ , the  
NNAE having a neural network generating the adaptive control signal  $v_{ad}$  based on the  
plant output signal  $y$  and the pseudo-control signal  $v_{ad}$  supplied as inputs to the  
neural network, the neural network generating the adaptive control signal  $v_{ad}$  by  
mapping the plant output signal  $y$  and a pseudo-control signal  $v$  to the adaptive control  
10 signal  $v_{ad}$  based on at least one basis function  $\phi$  and at least one connection weight  $W$   
that is an output signal from the neural network, the adaptive element using the  
training signal  $\delta$  to update the basis function  $\phi$  and at least one connection weight  $W$   
of the neural network so that the adaptive control signal  $v_{ad}$  generated by the neural  
network is bounded.

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9. An ACS as claimed in claim 8 wherein the LDC maps the tracking error  
signal  $\tilde{y}$  to the pseudo-control component signal  $v_{dc}$  based on a transfer function  
 $N_{dc}(s)/D_{dc}(s)$ , and the LDC maps the tracking error signal  $\tilde{y}$  to the transformed  
signal  $\tilde{y}_{ad}$  based on a transfer function  $N_{ad}(s) / D_{dc}(s)$ , the transfer functions  
20  $N_{dc}(s)/D_{dc}(s)$  and  $N_{ad}(s) / D_{dc}(s)$  selected to assure boundedness of the tracking  
error signal.

10. An ACS as claimed in claim 8 further comprising:

25 a delay element coupled to receive the plant output signal  $y$  and  
generating at least one delayed plant output signal  $y_d$  as an additional input signal to  
the neural network to generate the adaptive control signal  $v_{ad}$ .

11. An ACS as claimed in claim 8 further comprising:

30 a delay element coupled to receive the pseudo-control signal  $v$  and  
generating at least one delayed pseudo-control signal  $v_d$ , the delay element coupled to

supply the delayed pseudo-control signal  $v_d$  as an additional input signal to the neural network to generate the adaptive control signal  $v_{ad}$ .

5        12. An ACS as claimed in claim 8 wherein the plant comprises at least one sensor sensing at least one state of the plant, and generating the plant output signal  $y$  based on the sensed plant state.

10      13. An ACS as claimed in claim 8 wherein the plant comprises at least one actuator controlling the plant based on the command control signal  $\delta_c$ .

14. An ACS as claimed in claim 8 wherein the ACS is operated by a human operator, the ACS further comprising:

an operator interface unit coupled to receive the plant output signal  $y$ ,  
15    the operator interface unit generating a display signal based on the plant output signal  $y$ ;  
          the operator receiving the display signal from the operator interface unit, and producing control action to control the plant based on the display signal; and  
          a command filter unit operable by the operator, the command filter unit  
20    generating the commanded output signal  $y_c$  and optional derivatives thereof, and the  $r$ th derivative  $y_c^{(r)}$  of the plant output signal  $y$  based on control action of the operator.

15. An ACS as claimed in claim 8 further comprising:

an operator interface unit coupled to receive the plant output signal  $y$ ,  
25    the operator interface unit generating a signal based on the plant output signal  $y$ ;  
          an operator coupled to receive the signal generated by the operator interface unit, and generating an operator signal to control the plant based on the signal generated by the operator interface unit; and  
          a command filter unit operable by the operator, the command filter unit  
30    generating the commanded output signal  $y_c$  and optional derivatives thereof, and the  $r$ th derivative  $y_c^{(r)}$  of the plant output signal  $y$  based on the operator signal.

16. A linear controller coupled to receive a tracking error signal  $\tilde{y}$  that is a vector difference of a plant output signal  $y$  that is a function of a full plant state having known but unrestricted relative degree  $r$ , and a commanded output signal  $y_c$ , the linear controller generating a pseudo-control component signal  $v_{dc}$  based on a transfer function  $N_{dc}(s)/D_{dc}(s)$  and the tracking error signal  $\tilde{y}$ , the pseudo-control component signal  $v_{dc}$  used by the linear controller to control the plant based on an approximate linear model, and the linear controller generating a transformed signal  $\tilde{y}_{ad}$  based on a transfer function  $N_{ad}(s)/D_{dc}(s)$  and the tracking error signal  $\tilde{y}$ , the transformed signal  $\tilde{y}_{ad}$  used for adaptive control of the plant, the transfer functions  $N_{dc}(s)/D_{dc}(s)$  and  $N_{ad}(s)/D_{dc}(s)$  selected to assure boundedness of the tracking error signal.

17. An adaptive element (AE) of an adaptive control system (ACS) for controlling a plant based on a plant output signal  $y$  that is a function of the full plant state existing in a plant, a pseudo-control signal  $v$  used to control the plant, and a 5 transformed signal  $\tilde{y}_{ad}$  from a linear controller of the ACS, the adaptive element comprising:

10 a neural network adaptive element (NNAE) comprising a neural network having at least one connection weight  $W$  and at least one basis function  $\phi$ , the neural network coupled to receive the pseudo-control signal  $v$  and the plant output signal  $y$ ;

15 a delay element coupled to receive the plant output signal  $y$  and the pseudo-control signal  $v$ , and generating signals  $y_d$ ,  $v_d$  that are delayed versions of the plant output signal  $y$  and the pseudo-control signal  $v$ ; and

20 an error conditioning element coupled to receive the transformed signal  $\tilde{y}_{ad}$  and the basis function  $\phi$ , and generating an error signal  $\delta$  based thereon,

25 the NNAE coupled to receive the error signal  $\delta$  and adapting the connection weight  $W$  and the basis function  $\phi$  to adaptively control unmodeled plant dynamics.

18. An adaptive element as claimed in claim 17 wherein the error conditioning element includes a filter and a multiplier, the filter operating on the basis function  $\phi$  from the NNAE to produce a filtered basis function  $\phi_f$ , the multiplier generating the error signal  $\delta$  by multiplying the filtered basis function  $\phi_f$  by the transformed signal  $\tilde{y}_{ad}$ .

19. An adaptive element as claimed in claim 18 wherein the filter operates on the basis function  $\phi$  to produce the filtered basis function  $\phi_f$  using a transfer function  $T^{-1}(s)$  that ensures boundedness of the connection weight  $W$  and the tracking error signal.

20. A method comprising the step of:

- a) generating at least one command control signal  $\delta_c$  to regulate a plant output signal  $y$  by direct feedback of the plant output signal  $y$ , and optionally other sensed variables affecting the state of the plant,  $y$  being a function of the full plant state having known but unrestricted relative degree  $r$ .

21. A method as claimed in claim 20 wherein the control signal  $\delta_c$  is generated in step (a) so as to control the plant output based on an approximate linear dynamic model, and so as to control the plant output in spite of unmodeled plant dynamics based on an adaptive control technique.

22. A method as claimed in claim 20 wherein the adaptive control technique is implemented with a neural network.

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23. A method comprising the steps of:

a) selecting a transfer function  $N_{dc}(s)/D_{dc}(s)$  used in control of a plant based on a plant output signal  $y$  that is a function of all states existing in the plant, and

5 b) a transfer function  $N_{ad}(s)/D_{dc}(s)$  used in adaptive control of the plant based on the plant output signal  $y$ , to ensure boundedness of the tracking error signal.

24. A method comprising the steps of:

a) generating a tracking error signal  $\tilde{y}$  that is a vector difference of a plant output signal  $y$  that is a function of all states existing in a plant, and a commanded output signal  $y_c$ ;

10 b) generating a pseudo-control component signal  $v_{dc}$  based on a transfer function  $N_{dc}(s)/D_{dc}(s)$  and the tracking error signal  $\tilde{y}$ ; and

c) generating a transformed signal  $\tilde{y}_{ad}$  based on a transfer function

15  $N_{ad}(s)/D_{dc}(s)$  and the tracking error signal  $\tilde{y}$ .

25. A method as claimed in claim 24 further comprising:

d) controlling a plant with the pseudo-control component signal  $v_{dc}$ , the pseudo-control component signal  $v_{dc}$  controlling the plant based on an approximate linear model; and

20 e) controlling the plant adaptively based on the transformed signal  $\tilde{y}_{ad}$  used for adaptive control of the plant.

26. A method as claimed in claim 24 further comprising the steps of:

25 d) receiving a plant output signal  $y$  that is a function of all states existing in a plant;

e) delaying the plant output signal  $y$  to produce a delayed signal  $y_d$ ;

f) receiving a pseudo-control signal  $v$  used to control the plant;

30 g) delaying the pseudo-control signal  $v$  to produce a delayed signal  $v_d$ ;

and

h) supplying the signals  $y$ ,  $y_d$ ,  $v$ ,  $v_d$  to a neural network to generate an adaptive control signal  $v_{ad}$  to control the plant.

5 27. A method as claimed in claim 26 further comprising the steps of:

i) filtering at least one basis function  $\phi$  to generate a filtered basis function  $\phi_f$ ;

j) multiplying the filtered basis function  $\phi_f$  by the transformed signal  $\tilde{y}_{ad}$  to produce an error signal  $\delta$ ; and

10 k) modifying at least one connection weight  $W$  of the neural network based on the error signal  $\delta$ .

28. A method as claimed in claim 27 further comprising the steps of:

l) differentiating the plant output signal  $y$   $r$  times to produce an  $r$ th derivative signal  $y_e^{(r)}$  of the plant output signal  $y$ ,  $r$  being the relative degree of the plant output signal;

m) summing the  $r$ th derivative signal, the pseudo-control component signal  $v_{dc}$ , and the adaptive control signal  $v_{ad}$ , to generate a pseudo-control signal  $v$ ; and

20 n) generating a command control signal  $\delta_c$  based on the pseudo-control signal  $v$  and the plant output signal  $y$  by model inversion.

29. A method comprising the steps of:

a) receiving a plant output signal  $y$  that is a function of all states existing in a plant;

b) delaying the plant output signal  $y$  to produce a delayed signal  $y_d$ ;

c) receiving a pseudo-control signal  $v$  used to control the plant;

d) delaying the pseudo-control signal  $v$  to produce a delayed signal  $v_d$ ;

and

30 e) supplying the signals  $y$ ,  $y_d$ ,  $v$ ,  $v_d$  to a neural network to generate an adaptive control signal  $v_{ad}$  to assist a linear controller in controlling the plant.

5 30. A method as claimed in claim 29 further comprising the steps of:

f) filtering at least one basis function  $\phi$  to generate a filtered basis function  $\phi_f$ ;

g) multiplying the filtered basis function  $\phi_e$  by the transformed signal  $\tilde{Y}_{opt}$  to produce an error signal  $\delta$ ; and

10 h) modifying at least one connection weight  $W$  of the neural network  
based on the error signal  $\delta$ .